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Complementarity: Flavor Physics in the LHC Era

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Abstract. The LHC physics era is about to commence; here we discuss a complementary physics program that would be realized at a high luminosity flavor factory. A flavor factory experiment can search for new physics in CP asymmetries, inclusive decay processes, rare leptonic processes, absolute branching fractions, and other measurements that are challenging or not feasible at the LHC. Such measurements would provide good sensitivity to new physics phases, the presence of a charged Higgs, and supersymmetric couplings. The charged Higgs mass range probed is similar to that accessible at the LHC.

Keywords: CP violation, weak phases, supersymmetry, Higgs

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INTRODUCTION

Particle physics is now entering the era of the LHC: the experiments that will soon be running at this accelerator are expected to shed light on the mechanism of electroweak symmetry breaking and establish whether new particles and interactions are present. However, the high center-of-mass energy utilized by the LHC is not the only method to access new physics (NP); this can also be done at lower energies by studying decays of heavy flavors (D and B mesons, and τ leptons) with large data sets. The latter type of experiment is known as a “flavor factory” or often a “ B Factory” due to the prominent role played by B meson decays in understanding the Cabibbo-Kobayashi-Maskawa weak mixing matrix. In the LHC era, there is a unique and complementary role played by a flavor factory, and currently two groups are proposing to build such facilities: Belle-II [1] in Japan, which is an upgrade of the Belle experiment [2], and SuperB [3] in Italy, which is an evolution of the Babar experiment [4]. These proposed experiments will nominally record 20-50 times the amount of data recorded by Belle and Babar, with the goal of addressing the following issues: are there more than three generations? Why are quark masses so different? Why is there such an unusual pattern of CKM weak coupling strengths, and what causes the phase in the CKM matrix? Is this the only phase present? Given the small amount of CP violation observed in K and B decays, why is our universe overwhelmingly matter-dominated?

A flavor factory can search for NP in CP asymmetries, inclusive decay processes, rare leptonic decays, absolute branching fractions, and other processes not easily accessible at the LHC. A flavor factory probes processes that occur at 1-loop in the Standard Model (SM) but may occur at tree level in NP scenarios; such SM-loop processes probe energy scales that cannot be accessed directly at the LHC. If supersymmetry is in fact observed at the LHC, a crucial question will be: how is it broken? By making detailed studies of

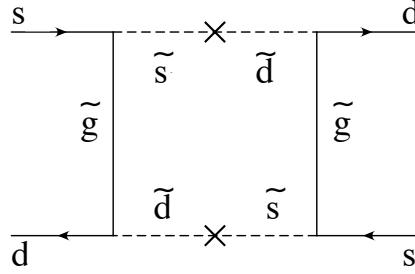


FIGURE 1. A $\Delta F = 2$ gluino-squark diagram.

flavor couplings, a flavor factory can address this.

Most scenarios of new physics can be classified as either supersymmetric theories, little Higgs models, models with extra dimensions, left-right models, or strongly coupled models [5]. All of these have implications for flavor physics. For example, consider the $\Delta F = 2$ gluino-squark diagram shown in Fig. 1. This diagram can give rise to neutral meson mixing. By dimensional considerations, the effective four-quark operators governing such mixing must have the form $(C_{NP}/\Lambda_{NP}^2)[\bar{d}_{jL}\gamma_\mu d_{iL}]^2$ plus other possible chirality structure, where Λ_{NP} is the energy scale associated with NP, and C_{NP} is a NP Wilson coefficient of $O(1)$. The corresponding term in the SM, e.g., for $B^0-\bar{B}^0$ mixing, is

$$\left(\frac{g^2}{8\pi M_W}\right)^2 (V_{td}^* V_{tb})^2 [\bar{d}_L \gamma_\mu b_L]^2 \approx \frac{(\sin^3 \theta_c)^2}{(2 \times 2.5 \text{ TeV})^2} [\bar{d}_L \gamma_\mu b_L]^2. \quad (1)$$

Since we do not yet observe NP effects, the NP operator must be less than the SM term (1), or equivalently $\Lambda_{NP} > \sqrt{C_{NP} \cdot 4 \cdot (2.5 \text{ TeV})^2 / (\sin^3 \theta_c)^2} \sim 400 \text{ TeV}$. The fact that this scale is much larger than the weak scale is a manifestation of the “flavor problem:” new physics needed at the TeV scale to stabilize the electroweak symmetry-breaking scale must have a highly non-generic flavor structure.

For most NP models, the coupling strengths across generations are not predicted. If one assumes that the only source of flavor-changing neutral currents (FCNC) is the Yukawa couplings – and there is no *a priori* reason why this should be so – then the FCNC are CKM-suppressed. For example, for $B^0-\bar{B}^0$ mixing

$$H_{NP}^{\text{eff}} \approx \frac{C_{NP}}{\Lambda_{NP}^2} (V_{td}^* V_{tb})^2 [\bar{d}_L \gamma_\mu b_L]^2, \quad (2)$$

which implies $\Lambda_{NP} > \sqrt{C_{NP} \cdot 4 \cdot (2.5 \text{ TeV})^2} \sim 5 \text{ TeV}$. This scenario is known as “Minimal Flavor Violation.” Although it substantially lowers the scale at which NP could appear, the scale remains higher than what the LHC can comfortably probe.

In the remainder of this paper we discuss five types of measurements for which a flavor factory has excellent potential for identifying NP if present: (a) measuring mixing phases; (b) measuring decay phases; (c) detecting a charged Higgs via leptonic decays; (d) identifying new physics via $b \rightarrow s$ transitions; and (e) determining how supersymmetry is broken via measurements of $\sin 2\phi_1$ (a combination of weak and decay

phases). Here we limit our discussions to B decays, but a flavor factory also produces prodigious amounts of D and τ^\pm decays and will also use these to search for NP.

NEW PHYSICS IN MIXING PHASES

A flavor factory can measure weak mixing phases, which is a phase that enters a $B^0\bar{B}^0$ “oscillation” amplitude. In the SM such amplitudes consist of $\Delta B = 2$ loop diagrams and thus are especially sensitive to NP. The original goal of Belle and Babar was to measure the phase $\phi_1 \equiv \text{Arg}(-V_{cb}^* V_{cd} / V_{tb}^* V_{td})$, whose size is mainly determined by the mixing phase $\text{Arg}(V_{tb}^* V_{td})$. The method is as follows: a B^0 oscillates to a \bar{B}^0 and subsequently decays to a self-conjugate final state that a B^0 can decay to directly. This amplitude (due to mixing), as compared to the direct amplitude, contains an additional weak phase (that of mixing). The two amplitudes interfere, and the interference term in the decay rate is proportional to the sine of twice the overall weak phase. Thus, measuring the decay time dependence allows one to fit for the interference term and determine this weak phase.

Applying the method to high-statistics $B^0 \rightarrow J/\psi K_S^0$ and other $b \rightarrow c\bar{c}s$ decay channels measures the phase ϕ_1 ; the result is $\sin 2\phi_1 = 0.670 \pm 0.023$ [6]. This method has been extended to $b \rightarrow s\bar{s}\bar{s}$ and $b \rightarrow s\bar{d}\bar{d}$ penguin decay modes, which should have the same overall weak phase (ϕ_1) up to small corrections of $O(\sin^2 \theta_C)$. The results are tabulated in Fig. 2; also shown for comparison is the world average value measured from $b \rightarrow c\bar{c}s$ decays. The table shows a systematic shift for $b \rightarrow s\bar{q}\bar{q}$ to lower values, although the current statistical errors preclude drawing a firm conclusion. However, most theoretical predictions prefer a shift to *higher* values (see Fig. 3); this difference could be a sign of a new non-SM phase. A future flavor factory should clarify this, as the expected statistical improvement in measuring $\sin 2\phi_1$ from $b \rightarrow s\bar{q}\bar{q}$ decays is a factor of 5–10.

NEW PHYSICS IN DECAY PHASES

A flavor factory can also search for new physics (NP) in *decay* phases, i.e., phases that appear directly in a $b \rightarrow q$ decay amplitude (no $B^0\bar{B}^0$ mixing is needed). Decay phases give rise to direct CP violation, i.e., a difference between $\Gamma(B \rightarrow f)$ and $\Gamma(\bar{B} \rightarrow \bar{f})$ due to interference between two or more decay amplitudes (e.g., penguin and tree) with different weak phases. Explicitly, if $B \rightarrow f$ proceeds via a tree amplitude $\mathcal{A}_t = |A_t| e^{i(\phi_t + \delta_t)}$ and a penguin amplitude $\mathcal{A}_p = |A_p| e^{i(\phi_p + \delta_p)}$, where ϕ and δ are weak and strong phases, respectively, then $\bar{B} \rightarrow \bar{f}$ proceeds via $|A_t| e^{i(-\phi_t + \delta_t)}$ and $|A_p| e^{i(-\phi_p + \delta_p)}$. Summing the amplitudes and squaring gives decay rates $R = |A_t|^2 + |A_p|^2 + 4|A_t||A_p|\cos(\Delta\delta \pm \Delta\phi)$, where $\Delta\delta = \delta_t - \delta_p$ and $\Delta\phi = \phi_t - \phi_p$. Taking the sums and differences of the decay rates gives

$$A_{CP} \equiv \frac{\Gamma(B \rightarrow f) - \Gamma(\bar{B} \rightarrow \bar{f})}{\Gamma(B \rightarrow f) + \Gamma(\bar{B} \rightarrow \bar{f})} \propto \sin \Delta\phi \sin \Delta\delta. \quad (3)$$

Thus a direct CP asymmetry arises only if the two contributing decay amplitudes have different weak (ϕ) and strong (δ) phases.

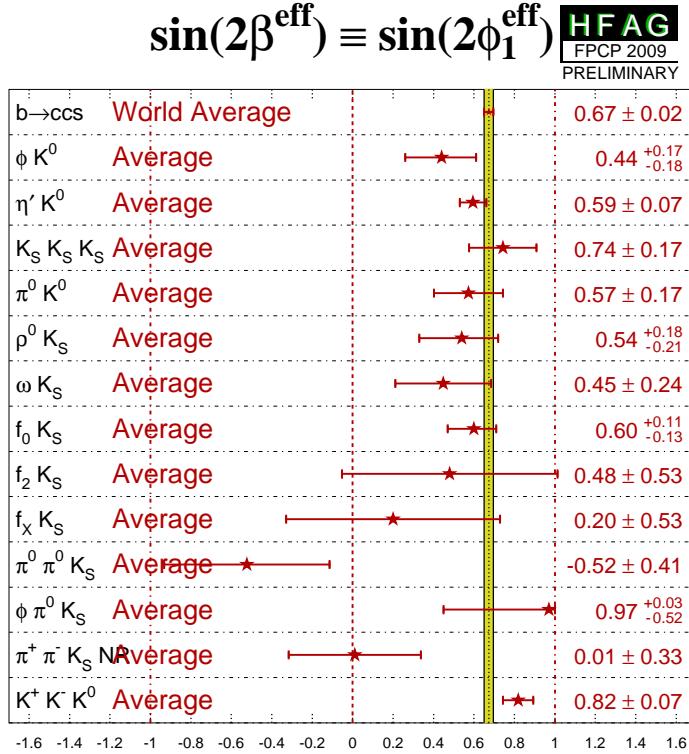


FIGURE 2. World average values of $\sin 2\phi_1$ measured using various decay modes (left), from the Heavy Flavor Averaging Group (HFAG) [6]. The $b \rightarrow c\bar{c}s$ value is dominated by $B^0 \rightarrow J/\psi K_S^0$ decays.

The charmless decays $B \rightarrow K\pi$ proceed via both tree and penguin amplitudes and, because the final states are self-tagging, are well-suited for measuring A_{CP} . The two amplitudes for the neutral decay $B^0 \rightarrow K^+\pi^-$ are shown in Figs. 4a and 4b; the measured CP asymmetry is $-0.098^{+0.012}_{-0.011}$ [8]. The analogous diagrams for the charged decay $B^+ \rightarrow K^+\pi^0$ are shown in Figs. 4c and 4d; as these have the same weak and strong phases as those for B^0 decay, A_{CP} should be the same. However, the result for B^+ is 5.3σ away: $A_{CP} = 0.050 \pm 0.025$ [8]. This discrepancy may indicate the presence of a new phase entering one of the decay amplitudes, e.g., in an NP-enhanced electroweak penguin [9]. A future flavor factory can clarify this.

DETECTING A CHARGED HIGGS

A flavor factory in fact has similar sensitivity to a charged Higgs boson as does the LHC, but in complementary search channels. A charged Higgs would manifest itself in inclusive $b \rightarrow s\gamma$ decays, and in exclusive $B^+ \rightarrow \tau^+\nu$ and $B^0 \rightarrow D^{*-}\tau^+\nu$ decays. Although these final states are challenging to reconstruct due to missing particles, both Belle and Babar have reconstructed first samples [10, 11] and a flavor factory would increase these substantially.

For inclusive $b \rightarrow s\gamma$ decays, one requires the presence of a high momentum photon

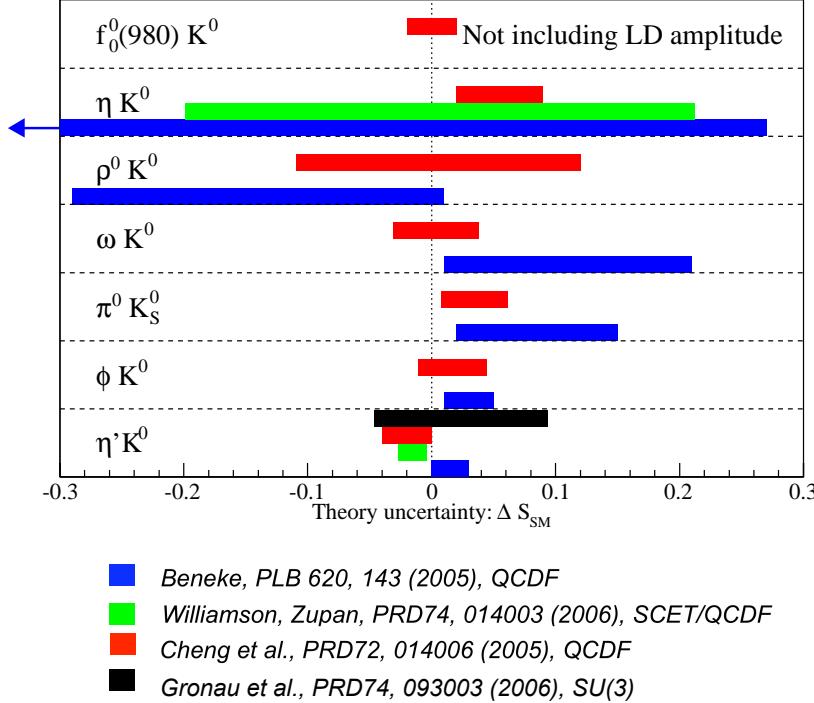


FIGURE 3. Compilation of theoretical predictions for $\Delta S \equiv (\sin 2\phi_1)_{q\bar{q}s} - (\sin 2\phi_1)_{c\bar{c}s}$, from Ref. [7].

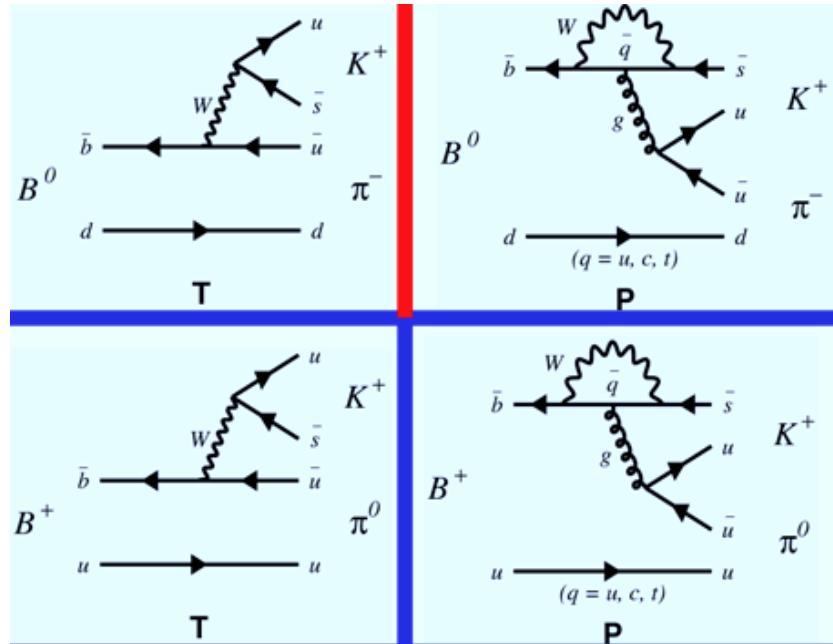


FIGURE 4. Tree amplitude (upper left) and penguin amplitude (upper right) contribution to $B^0 \rightarrow K^+ \pi^-$; tree amplitude (lower left) and penguin amplitude (lower right) contribution to $B^+ \rightarrow K^+ \pi^0$.

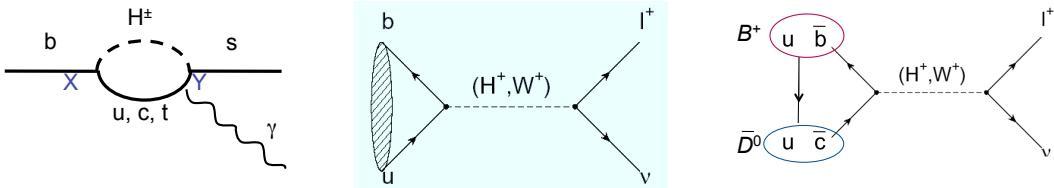


FIGURE 5. Charged-Higgs-mediated diagrams for $b \rightarrow s\gamma$ (left), $B^+ \rightarrow \tau^+\nu$ (middle), and $B^+ \rightarrow \bar{D}^{(*)0}\tau^+\nu$ (right).

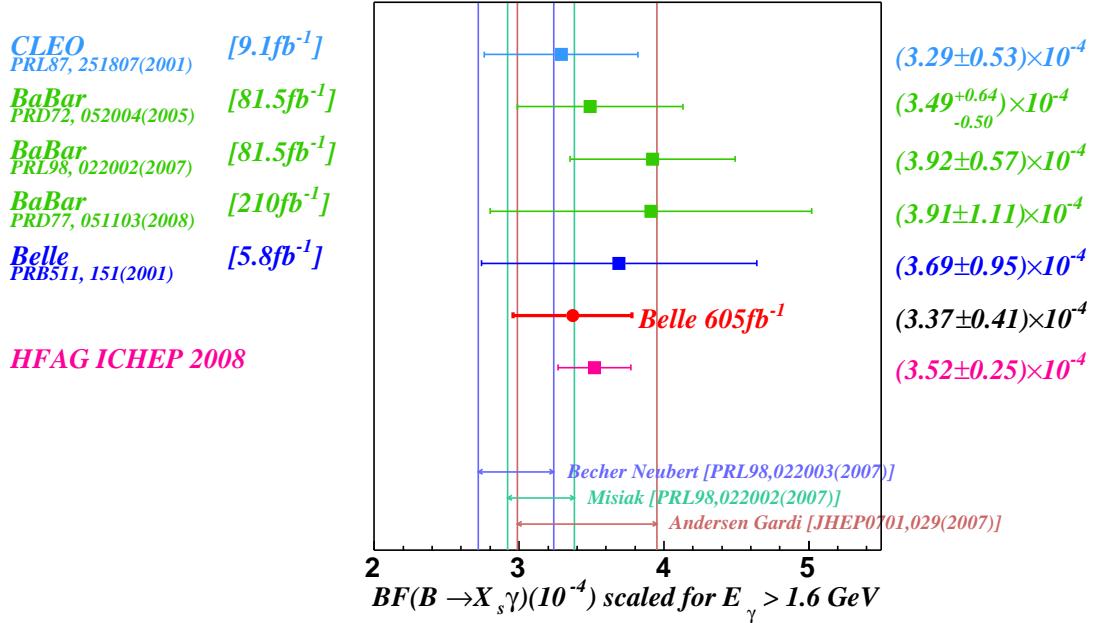


FIGURE 6. Compilation of measurements of the inclusive process $b \rightarrow s\gamma$.

and a charged kaon. The charged-Higgs-mediated diagram for this decay is shown in Fig. 5a. Various measurements are tabulated in Fig. 6; the world average (WA) branching fraction is $(3.52 \pm 0.25) \times 10^{-4}$ [12]. An upper limit on the branching fraction sets a lower limit on M_H ; this is illustrated in Fig. 7, which plots the limit as a function of the branching fraction central value and error. The plot corresponds to all values of $\tan\beta$, where β is the ratio of vacuum expectation values for the two Higgs fields and is an unknown model parameter. From the figure one reads that the current WA branching fraction corresponds to a 95% C.L. lower bound $M_{H^+} > 300 \text{ GeV}/c^2$. At a future flavor factory, this bound may increase to more than $500 \text{ GeV}/c^2$, depending on the branching fraction central value.

A charged Higgs also affects $B^+ \rightarrow \tau^+\nu$ decays; the relevant diagram is shown in Fig. 5b. The analysis is challenging because the signal side has two missing neutrinos and thus cannot be fully reconstructed. The Belle result is $\mathcal{B}(B^+ \rightarrow \tau^+\nu) = (1.65_{-0.37}^{+0.38}_{-0.37}) \times 10^{-4}$ [10]; dividing by the SM prediction $\mathcal{B}_{SM} = (0.796_{-0.093}^{+0.154}) \times 10^{-4}$ [14] yields $r_H \equiv \mathcal{B}_{\text{measured}}/\mathcal{B}_{SM} = 2.07 \pm 0.74$ [15]. Theoretically, in a two-Higgs doublet model $r_H = (1 - M_B^2 \tan^2 \beta / M_H^2)^2$ [16]; an upper limit on r_H thus gives a lower

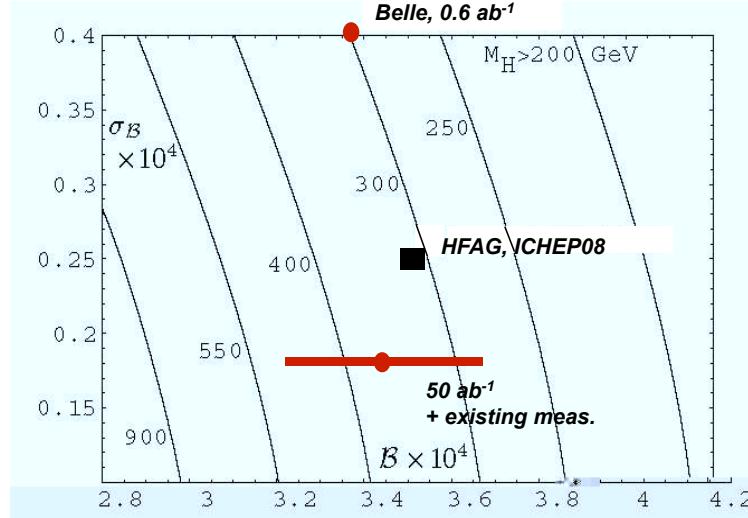


FIGURE 7. 95% C.L. lower limits on M_{H^+} as a function of the central value and error for $\mathcal{B}(b \rightarrow s\gamma)$, from Ref. [13].

limit on M_H that depends on $\tan\beta$. The result is shown in Fig. 8a, where the shaded region is excluded. The allowed region (light band) in the middle of the shaded region results from a dip in r_H near $(\tan\beta/M_H) \approx 1/M_B$. This “gap” will be closed by measurements at a flavor factory of $B \rightarrow D^* \tau^+ \nu$ decays. The amplitude for this is governed by the $b \rightarrow c$ transition shown in Fig. 5c. The expected sensitivity of a flavor factory for 5 ab^{-1} and 50 ab^{-1} of data is shown in Fig. 8b; for large $\tan\beta$, most of the M_H range accessible to the LHC is covered [17].

IDENTIFYING SUPERSYMMETRY

Finally, we show that a flavor factory has surprisingly good sensitivity to supersymmetry. If the LHC observes signs of supersymmetry, measurements from a flavor factory could prove crucial for distinguishing among various theoretical models and determining the mechanism by which supersymmetry is broken.

Supersymmetric theories are challenging to experimentally confirm or exclude as there are many parameters to tune. For example, one way of calculating flavor-changing neutral-current (FCNC) processes in MSSM is to parameterize squark mass matrices with flavor-off-diagonal mass insertion terms. The corresponding sparticles can mediate SM-suppressed FCNC transitions such as $b \rightarrow s$. Thus, measuring $b \rightarrow s$ observables such as $\mathcal{B}(b \rightarrow s\gamma)$, $A_{CP}(b \rightarrow s\gamma)$, $\mathcal{B}(b \rightarrow sl^+\ell^-)$, and $A_{CP}(b \rightarrow sl^+\ell^-)$ can nominally constrain such mass-insertion terms. These observables should be well-measured at a future flavor factory. The expected constraints as a function of gluino mass are shown in Fig. 9. These plots correspond to 50 ab^{-1} of data, and the measurement of ΔM_s from hadron collider experiments CDF and D0 has been included. The shaded areas show the regions of parameter space that would be measured non-zero with at least 3σ

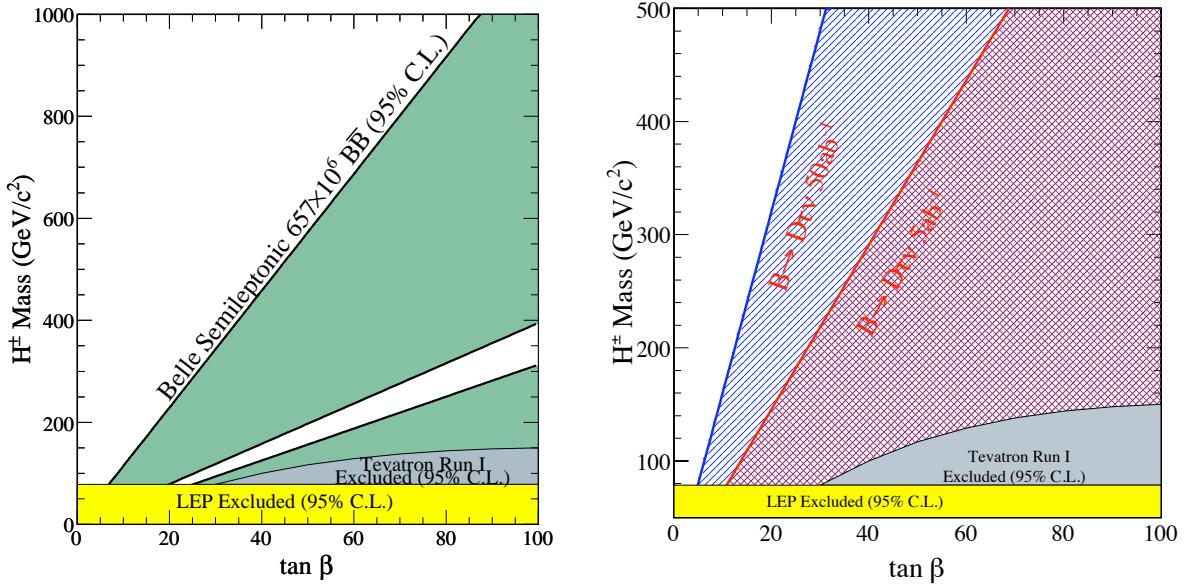


FIGURE 8. Excluded values of M_{H^\pm} (shaded regions) as a function of $\tan \beta$, from the upper limits on $\mathcal{B}(B^+ \rightarrow \tau^+ \nu)$ (left) [15] and $\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu)$ (right) [18]. In the right-most plot, the red (blue) shaded region corresponds to 5 ab^{-1} (50 ab^{-1}) of data.

statistical significance. These shaded regions cover about half the parameter space. For the restricted case of a light gluino ($M_{\tilde{g}} \lesssim 100 \text{ GeV}/c^2$), all values of mass insertions are covered.

A flavor factory can discriminate among different SUSY-breaking mechanisms via the observables $\Delta S = (\sin 2\phi_1)_{q\bar{q}s} - (\sin 2\phi_1)_{c\bar{c}s}$ and $(\sin 2\phi_1)_{K^0\pi^0\gamma}$. The results of a Monte Carlo calculation of ΔS and $(\sin 2\phi_1)_{K^0\pi^0\gamma}$ are shown in Figs. 10 and 11, respectively, for three models of SUSY-breaking: mSUGRA, SU(5) SUSY GUT, and MSSM+U(2). For each case a spread of points is shown; these result from sampling over distributions for theoretical parameters whose values are unknown. Superimposed on the plots is the error bar expected from measurements at a flavor factory for 50 ab^{-1} of data. One sees that, depending on the central values obtained, a flavor factory could distinguish among the models. For example, a central value of $(\sin 2\phi_1)_{K^0\pi^0\gamma} > 0.03$ would essentially rule out mSUGRA, and a large value $(\sin 2\phi_1)_{K^0\pi^0\gamma} \approx 0.10$ would favor SU(5) SUSY GUT with a small gluino mass.

SUMMARY

A flavor factory running in the era of the LHC would make very large – perhaps decisive – contributions to our understanding of beyond-the-SM physics. Such a facility would rigorously test our understanding of the SM (see Figs. 2 and 3), constrain the mass of a charged Higgs (Figs. 7 and 8), measure the values of supersymmetric mass insertion terms (Fig. 9), and possibly distinguish among different scenarios of supersymmetry breaking (Figs. 10 and 11). If supersymmetry is discovered at the LHC, a

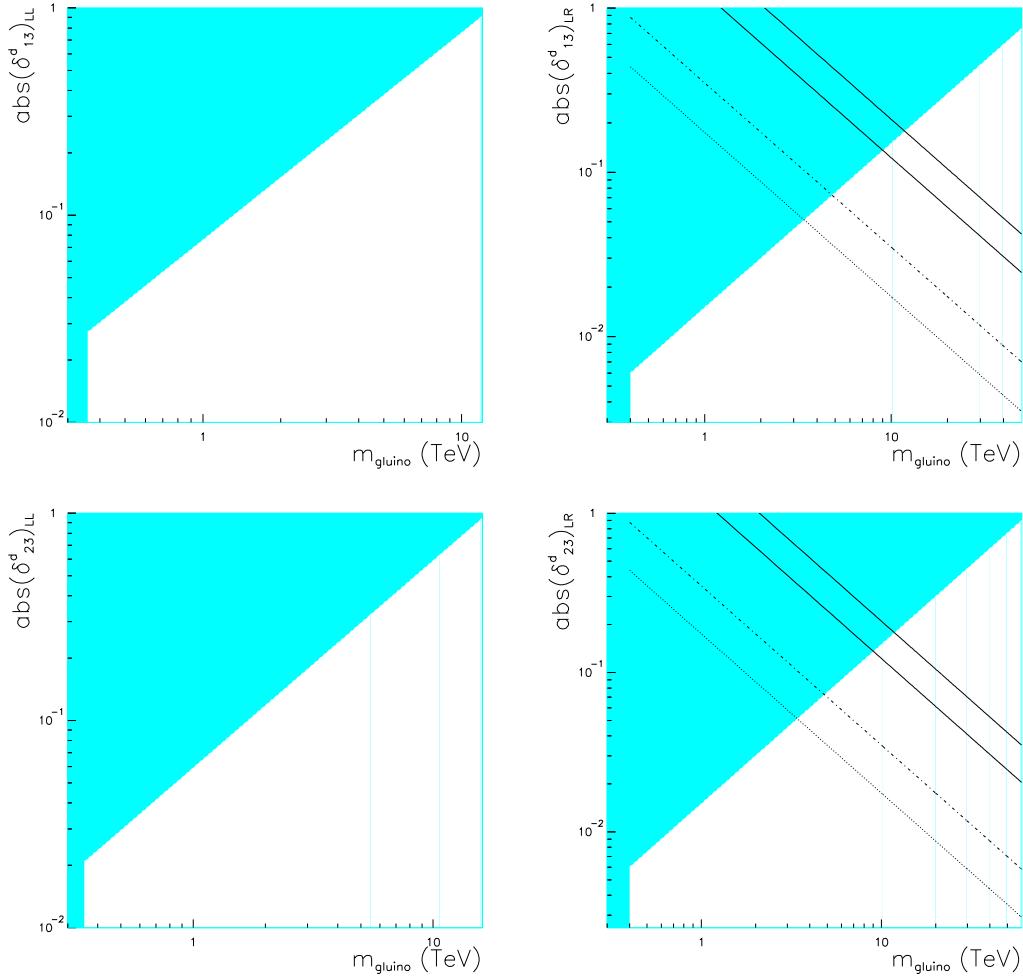


FIGURE 9. Values of mass insertion terms that would be measured non-zero with at least 3σ statistical significance (shaded regions), for 50 ab^{-1} of data [19]. The upper left plot is for $(\delta_{13})_{\text{LL}}$; the upper right plot for $(\delta_{13})_{\text{LR}}$; the lower left plot for $(\delta_{23})_{\text{LL}}$; and the lower right plot for $(\delta_{23})_{\text{LR}}$.

flavor factory may be necessary to determine how it is broken. In addition, a flavor factory can study D^0 - \bar{D}^0 mixing and search for CP violation in this system; a signal for the latter at the percent level would be a strong indication of NP. The clean environment of an e^+e^- flavor factory allows one to search for NP in forbidden τ^+ decays such as $\tau^+ \rightarrow \mu^+ \gamma$. A future flavor factory is needed to solve the flavor puzzles uncovered by the B -factory experiments Belle and Babar, e.g., $\sin 2\phi_1$ measured in $b \rightarrow sq\bar{q}$ loop processes is systematically lower than that measured in $b \rightarrow c\bar{c}s$ tree processes; and A_{CP} measured in charged $B^+ \rightarrow K\pi$ decays differs substantially from that measured in neutral $B^0 \rightarrow K\pi$ decays. These measurements are complementary to those that will be made at LHC experiments, which are based on higher- p_T triggers operating in high-multiplicity hadroproduction environments. Measurements made at a flavor factory may greatly increase our understanding of results from the LHC.

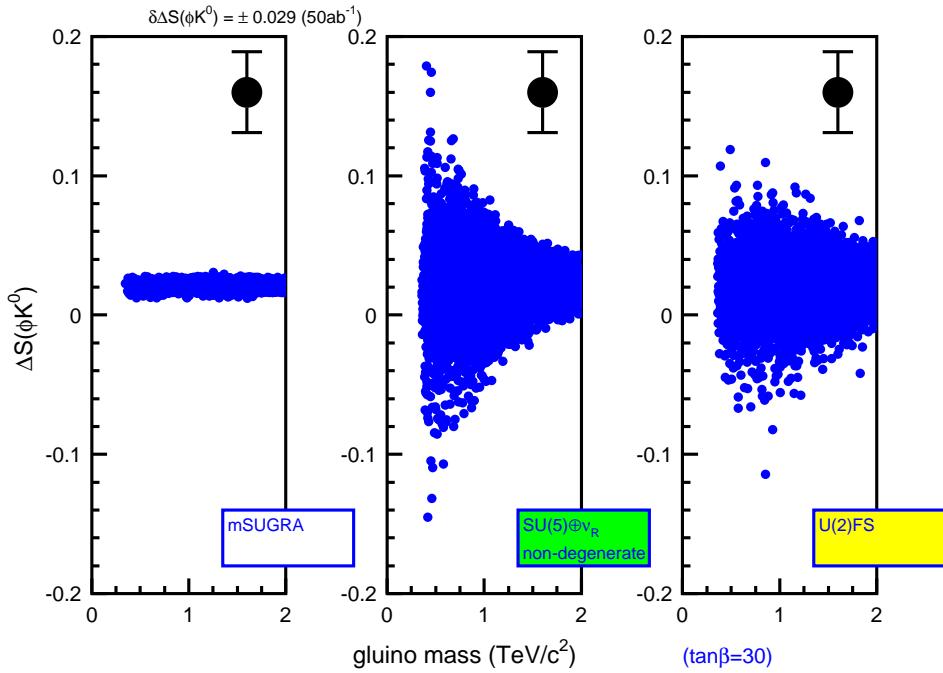


FIGURE 10. Predictions for ΔS (see text) for three supersymmetric theories: mSUGRA (left), SU(5) SUSY GUT (middle), and MSSM+U(2) (right). The data point shown illustrates the error expected from 50 ab^{-1} of data [18].

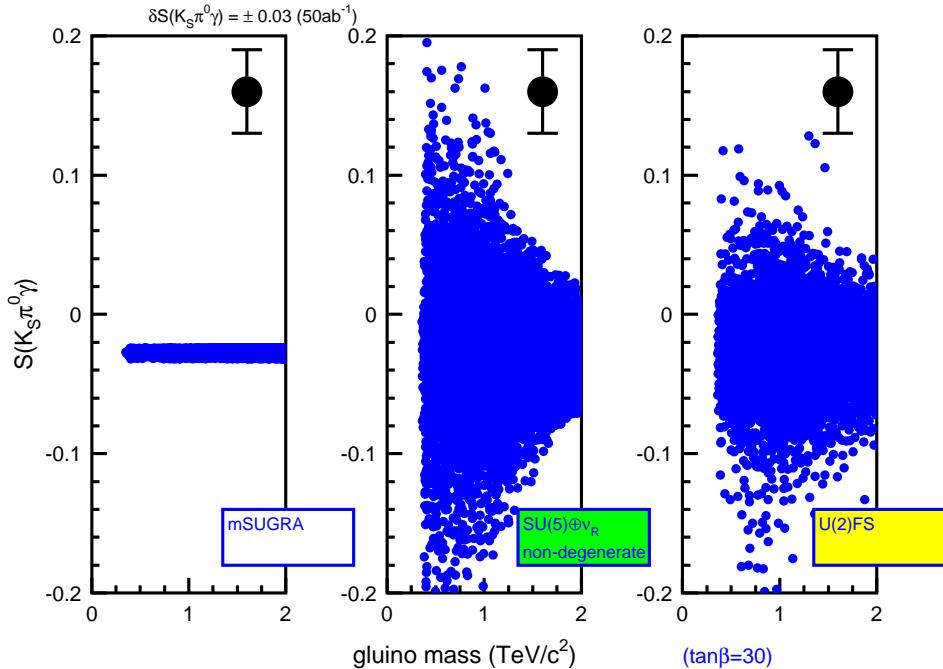


FIGURE 11. Predictions for $(\sin 2\phi_1)_{K^0\pi^0\gamma}$ for three supersymmetric theories: mSUGRA (left), SU(5) SUSY GUT (middle), and MSSM+U(2) (right). The data point shown illustrates the error expected from 50 ab^{-1} of data [18].

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